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# NAVSTAR AIRCRAFT AERIAL SYSTEM - SOME INITIAL CONSIDERATIONS

by

M. J. Sidford

## SUMMARY

Aircraft Aerial Systems for use with the US Navstar global positioning system are categorised, and initial design considerations are given for each category from simple omnidirectional aerials to systems with ECCM capabilities.

## CONTENTS

## 1 INTRODUCTION

The Navstar GPS, Satellite-based Navigation System is currently under development to be in service by the mid-1980s. The system employs 24 satellites in 12h inclined orbits to give continuous three-dimensional coverage of the Earth, and is described in Ref.1.

## 2 BASIC REQUIREMENTS

In ideal terms, the aircraft (user equipment) aerial system is required to receive signals from any four of a maximum of nine satellites visible at any instant, with a gain of 3dB (with respect to circularly polarised isotropic) for any feasible aircraft attitude. Furthermore the system should have the capability to reduce interference from an unspecified number of noise jammers situated in any direction relative to the aircraft/satellite geometry. When used with X-type (parallel processing) receivers, the aerial system will be required to provide simultaneous outputs to the four parallel satellite tracking channels of the receiver at both $L_1$ (1575MHz) and $L_2$ (1228MHz) carrier frequencies. With Y-type (sequential processing) receivers, the aerial system need look at only one satellite at a time, four satellites being viewed sequentially - again at both $L_1$ and $L_2$ frequencies. Similar sequential viewing is catered for with Z-type (reduced capability) receivers, but in this case only the $L_1$ frequency is required.

The severity of the requirement varies according to the aircraft role ranging from a simple system on a civil aircraft using a Z-type receiver, to a complex installation for a highly manoeuvrable combat aircraft operating in a severe ECM environment. A range of possible solutions will therefore require investigation, and the cost effectiveness of the more complex systems will have to be judged against the employment of alternative ECCM techniques (e.g. narrowing of bandwidth involving integration with inertial navigation systems).

## 3 CATEGORIES OF AERIAL SYSTEM (Illustrated in Figs.1 to 6)

### 3.1 Simple omnidirectional system (Category A)

This would provide upper hemisphere coverage with gain exceeding 0dB for some 70% of the hemisphere with the aircraft in level flight. No signal processing, aircraft attitude sensing or satellite direction information is required by the aerial system.

### 3.2 Attitude corrected omnidirectional system (Category B)

A number of aerials are sited on the airframe, the one giving optimum upper hemisphere coverage being chosen automatically from aircraft attitude information. Apart from a simple multiway PIN diode RF switch, no RF signal processing or knowledge of satellite directions is required.

### 3.3 Sector coverage systems (Category C)

A number of fixed beam aerials are installed on an aircraft to cover the hemisphere. Selection of the best aerial for a particular satellite/receiver channel is based on aircraft attitude and knowledge of satellite direction. Jamming in any one direction, recognised by a large reduction of output S/N for the channel associated with a particular beam, may in general be reduced by selection of a satellite in a widely different direction (and hence in a different beam).

### 3.4 Phased arrays - geometrically controlled (Category D)

One or more arrays of aerial elements are phased to produce beams in the known directions of the appropriate satellites. For X-type receivers, four beams are formed simultaneously, each beam output being routed to the appropriate receiver channel. For Y and Z type receivers, beam selection is made sequentially, to look at one satellite after another. Knowledge of the aircraft attitude is required in computing beam directions.

### 3.5 Phased arrays - adaptive null steering type (Category E)

The phase and amplitude weightings required to maximise strong jamming signals arriving from discrete directions are determined by correlation processes. Conjugate weighting is applied to array elements in the signal channels to null-out the interfering signals. The system depends on a high jam/signal ratio to avoid nulling in wanted signal directions. In the absence of jamming the array element weighting automatically adjusts to give an omnidirectional pattern. Provided that the aerial array can adapt rapidly, no information on the direction of satellites or the aircraft attitude may be needed in this system. Some satellite/jammer geometries will of course lead to low gain from the aerial system in the wanted signal directions.

### 3.6 Phased arrays - adaptive S/N optimisation type (Category F)

The signals from array elements are weighted in phase and amplitude to maximise the S/N in any one receive channel. The feedback to the weighting

circuits is achieved adaptively by 'hill climbing' processes using the receiver channel output S/N. The system effectively forms the aerial array pattern which best discriminates against jammer directions in favour of wanted signal directions. (Jamming signals are assumed to be random noise.) Again, given sufficient speed of adaptation, no input from aircraft attitude sensors or from satellite geometry computers may be required in this system.

### 3.7 Hybrid systems

Systems may be envisaged which do not fall into any single category listed above. For example, one or two fixed beam aerials (Category C) may be used to cover the higher elevation regions where the likelihood of jamming is presumably smaller than it is near the horizontal plane. An adaptive S/N optimisation system (Category F) may be added to cover these lower elevation regions. A further example would be to use a crude interferometer system to determine directions of jammers and to use this information together with known directions of satellite to choose optimum aerial beam/satellite combinations to combat the jamming.

## 4 AERIAL SYSTEM DESIGN CONSIDERATIONS

### Category A

Brief specification:-

| | | |
|---|---|---|
| Frequency bands | 1575 ± 10MHz | ($L_1$) |
| | 1228 ± 10MHz | ($L_2$) |

For Z-type receivers, $L_1$ only required.
For X and Y-type receivers, $L_1$ and $L_2$ coverage required.
VSWR in band 1.5:1.
Gain: 3dB nominal (relative to RHC isotropic).

Such a specification should not be difficult to achieve with a simple aerial. For $L_1$ use only, a printed circuit cavity backed crossed slot less than ¼in thick and conforming with the aircraft contour should be practicable.

According to scale model measurements, a crossed slot mounted on top of a 707 aircraft gives a peak gain of about 5dB at the zenith dropping to 0dB at elevation angles of around 15$^{\circ}$. The 'average' gain in the azimuth plane is -2 to -3dB. On smaller aircraft, low elevation coverage will not be quite as good, and close proximity to the tail plane, etc. will cause break-up of the pattern in some directions.

On the 707 the gain at $-10^{\circ}$ elevation relative to that at $+10^{\circ}$ is in the range -7 to -12dB. Hence some useful discrimination against ground based jammers may be expected with the aircraft in level flight.

Coverage of both $L_1$ and $L_2$ frequencies requires the use of separate crossed slot elements of the very shallow 'paste-on' variety, or a wider band single unit which will probably require a deeper cavity. An element which attempts to achieve the bandwidth (1218 to 1585MHz) by means of ridges in the cavity has been constructed at RAE, and preliminary results suggest that an aerial size of 18cm × 18cm × 2cm deep will meet the requirements.

Transmissions from other aircraft systems (UHF, 225-400MHz, 20 watts; L-band secure data link (if adopted) and possible TACAN replacement 960-1215MHz spread spectrum 200 watts; L-band AEROSAT (mainly Civil applications) 1640-1660MHz, 200 watts) must be rejected to a level below the onset of non-linear behaviour of the Navstar aerial preamplifier. This requires a low insertion loss filter designed in conjunction with the aerial, which might well be incorporated in the same unit. Incorporation of preamplifier is also a possibility, although servicing and replacement problems usually dictate that active units are mounted in an accessible location inside the airframe.

Category B

As mentioned, a top mounted crossed-slot aerial will have a sharp cut-off in its radiation pattern below the horizontal plane. Consequently low elevation satellites may well suffer reductions of 20dB in S/N in some directions during, say, a $40^{\circ}$ bank turn. It may well be that such degradation is acceptable over short intervals of time, particularly when Inertial Navigation systems inputs allow rapid resynchronisation after short breaks. If IN systems are not fitted, or if jamming activity makes resynchronisation difficult, it may be necessary to fit more than one aerial. For example if aerials are fitted one on the top centre line and one each side of the fuselage at $30^{\circ}$ around from the top, it should be possible to view satellites at $15^{\circ}$ elevation over a range of bank angles from $-45^{\circ}$ to $45^{\circ}$ without severe degradation. It is assumed that pitch angles of this order will occur much less frequently, but if necessary further nose and tail mounted units could be used. Aircraft pitch, bank and roll information with fairly crude accuracy is required for automatic selection of the best aerial. The use of separate preamplifiers for each aerial may not be necessary provided cable runs to the PIN diode selector switch are not too long (typically losses per 10ft run are 0.6 to 1.0dB). If the aerials are widely separated and cable lengths

widely different for each aerial, corrections will need to be made in the central processor to refer computed positions to a fixed point on the aircraft.

Category C

An example of the system in this category would be a 'belt array' where the aircraft fuselage is encircled with a belt of printed circuit very shallow profile elements. A 6ft diameter fuselage would require about 54 $\lambda/2$ elements which when connected in threes would produce 18 beams covering $360^{\circ}$ in the roll plane, overlapping at about -2 to -4dB below peak level depending on the elements used. The 18 beam outputs could be routed in the stripline 'belt' to a central point for switching. The latter should preferably be incorporated in the belt using PIN diodes, so that only dc control wires and 4 RF connectors (one to each receive channel) need penetrate the fuselage. The switching matrix should allow connection of any three element array output to any one of the four receive channel inputs, one preamplifier being required for each channel. No two beam outputs should ever be required simultaneously in any one receive channel and hence relative phase between array outputs is immaterial. In some cases two receive channels may have to share one beam output resulting in a loss of 3dB. Only very rarely will all four satellites lie in the same beam, when the loss would be 6dB.

A peak directivity of about 9dB is expected with this system. Microstrip 'patch' antennae have efficiencies of typically 70% (-1.5dB) and an average loss in microstrip lines prior to the switch would be about 1dB. Allowing a further 1.5dB for PIN diode switch loss, this gives a peak system gain of 5dB where no more than one array output is connected to each receive channel mixer. Where two satellites appear in the same beam this is reduced to 2dB as mentioned above.

It is likely that considerable pattern disturbance due to the wings will occur for arrays on the fuselage sides. Furthermore $\lambda/2$ microwave patch aerials have a 3dB beamwidth of typically about $90^{\circ}$ resulting in unacceptable performance in nose and tail directions. Crossed slot elements should be considered to improve this situation, but it is still likely that conical sectors in nose and tail directions will require the use of fixed beam 'blade' type aerials, one mounted above the nose and another under the rear section of the fuselage. A blade about 20cm high could accommodate a linearly polarised dipole-plus-monopole backed by a reflector giving a peak gain of about 5dB above circularly polarised isotropic.

The main advantage of this system is that the aircraft shape is used to direct beams in a direction normal to the local surface - i.e. no phase shifting is required, and beams formed from individual arrays have intrinsically low side-lobe levels (particularly if some amplitude weighting is incorporated). Lobing will inevitably occur in beams which strongly illuminate wing or tail plane structures, but for a belt array mounted well forward of the wings, this will occur mainly in the rearward sector covered by a blade dipole/monopole with reflector.

The design of a microstrip patch aerial will require development effort. References do exist to L-band elements and to dual frequency designs at VHF[2], but we have no clear understanding of how the various design parameters affect bandwidth, polarisation, radiation pattern and efficiency.

Category D

Examples of phased arrays at L-band exist from work on AEROSAT. The RAE system which has been developed by BAC[3] steers a beam in the roll plane and uses a conformal three element array of slot-dipoles on each shoulder of the fuselage to achieve this. A similar approach for the receive-only mode of AEROSAT has been used in an eight element microstrip patch aerial developed in the USA[2]. The latter system has peak roll plane gain of about 12dB in comparison with 9dB from the RAE system but the beamwidth of the microstrip patch aerials results in lower gain than the slot-dipole system in directions making a shallow angle to fuselage. A Canadian design exists[4] in a highly developed form in which beam steering is accomplished from a longitudinal nine element array of 'bent-down' crossed-dipoles mounted under a 4in high radome mounted on top of the fuselage. Twenty-five conical shaped beams are formed varying from $40^\circ$ wide in the azimuth plane in end-fire directions to around $10^\circ$ in array broadside directions. Minimum gain of 6dB above $10^\circ$ elevation is claimed, with a 'nominal' gain of 10dB. Measured beam patterns (except over the main beam coverage) have not yet been seen, but sidelobe levels are likely to be high with $90^\circ$ phase shifter quantisation.

Provided the central Navstar processor can compute the beams required for particular satellites for the instantaneous aircraft attitude, and provided the 1575MHz frequency only is needed, these AEROSAT aerials may be employable with only minor modification. Only one beam at a time is formed, and the output would thus be suitable for sequential receivers only. System duplication in suitably scaled-up form would be required for 1228MHz operation.

When simultaneous reception of four satellites is required, beam-forming is required in four parallel channels. To avoid a 6dB loss in S/N, a pre-amplifier would be required behind each array element. These factors will inevitably lead to an expensive system and cost-effectiveness will hinge on ingenuity in the design of beam-formers. The computational problem of beam selection is no mean feat, and could at worst involve storage of the gain of each beam in $\theta,\phi$ co-ordinates over the whole sphere from model measurements for any particular aircraft.

Category E

Null steering aerial systems range in complexity from single rotatable cardioid or figure-of-eight patterns produced by variation of a single phase shifter, to multi-element adaptive arrays.

To illustrate the simpler system, consider a circularly symmetric field in which the phase of the radiation varies approximately linearly with direction (consider one plane only). Such a field may be generated approximately by a 'square' array of four monopoles with quadripole phasing ($0^o$, $90^o$, $180^o$, $270^o$). If an omnidirectional monopole is placed at the centre of the square, this will produce a phase which is independent of direction. Addition of array and single monopole outputs will therefore produce a null in one direction (Ref.5). Furthermore the coupling between monopole and array should be small since voltages induced in diagonally opposite array monopoles cancel on addition. Adjustment of the phase in the single element channel will steer the 'null', and adjustment of the amplitude will vary the depth of the null. This adjustment of phase and amplitude (or element weighting) will also allow nulling to some degree in directions away from the azimuth plane.

Practical realisations of a single-null aerial would probably utilise multimode aerials. For example, it should be possible to feed an annular slot to operate in several modes - Fig.7. Feeding the central disc as a top loaded monopole should give a radiation pattern similar to that shown in Fig.7b. Feeding the slot with a quadripole feed should give a pattern which is circularly polarised in the direction of the normal, becoming vertically polarised at shallow angles to the ground plane - Fig.7a. Combination of these modes with suitable weighting in one feed line should allow single null formation at low elevation angles, Fig.7c, whilst at the same time retaining coverage at high elevations. Weighting of the amplitude at each of the four quadripole feed points independently will allow the sharpness of the null to be varied at the expense of uniformity of gain in the remainder of the pattern. A further independent mode may be radiated by generating an opposite sense (i.e. clockwise instead of

anticlockwise) quadripole feed. The effect of this will be to produce a linearly polarised pattern with two nulls, i.e. a pattern similar to that from a rotatable linear slot will be produced, the rotation angle dependent on a single phase shift (Fig.7d).

Such multimode aerials should be investigated as a possible means of achieving cancellation of a single jammer in near azimuthal plane directions with a relatively cheap, compact system, whilst still maintaining good coverage of the higher elevation angles.

When several sources of interference have to be nulled out, multi-element arrays are needed. In general, n-1 independently steerable nulls are available from an n element linear array. Each element has to be supplied with a variable weighting device. This may be achieved by splitting the input signals into quadrature components weighting the amplitude of each component (e.g. with PIN attenuators) and recombining. To give a full $360^{\circ}$ phase variation of the recombined signal, a $180^{\circ}$ phase reversal device must also be incorporated in each quadrature channel. The weighting is controlled in an analogue feedback loop arranged so as to minimise the summed array output fed to the receiver. One aerial element could have fixed (zero) weighting so that in the absence of any directional signals, the array will attenuate out all the other elements, leaving an omnidirectional pattern. In the absence of any jamming sources, the array will, in time, adapt to produce pattern minima in the directions of the wanted signals. By adjusting time constants of correlation circuits, the latter will become insensitive to weak signals, and nulling will only occur in the directions of strong interfering signals. The 'nulls' will of course have finite angular width and there are physical constraints on the geometries for which nulls in directions of interference also allow usable gain to remain in the wanted directions.

The following factors will therefore need particular attention in any investigation of null steering arrays:-

(a) Performance as a function of the ratio of signal and jammer powers.

(b) Performance with several jamming signal directions.

(c) Resultant array patterns produced by linear and circular arrays when adapted to null in one or more directions.

If the system appears to give significant advantages in theory, the cost of implementing the system in practice will be dependent on design of weighting circuits, preamplifiers, and adaptive 'processors'. The latter may require computing time on the Navstar central processing unit.

Category F

The feasibility of using the output signal-to-noise information from the receiver (in dc form) in a control loop which adjusted element weights by an iterative process to obtain maximum output S/N requires further investigation. Convergence and stability of 'hill climbing' loops in the presence of interfering sources may be inadequate, or lead to stable but non-optimum solutions. This is particularly complicated when four receivers, each tuned to receive a single satellite are each attempting to control the array for optimum signal-to-noise output. In this case it is almost certain that the array elements will each require a preamplifier after which the signals are split into four channels with separate weighting and adaptive processing for each receive channel.

Since the Navstar CPU will give the directions of the wanted signals, it should be possible to set up the element weights for array pattern maxima in those directions. This information could in principle be used as a starting point for the adaptive process, and to constrain the excursions of weights during the adaptive process, hence improving convergence and stability.

## 5 CONTRIBUTIONS OF AERIAL SYSTEM TO NAVIGATIONAL ERRORS

Apart from the effects of low gain leading to noise dilution of the navigation signals, other factors could lead to significant errors. It is assumed that ground reflected multipath will be rejected by the system due to its time delay relative to the direct signal (though presumably the possibility of obtaining a false 'lock-up' in a strong multipath environment cannot be ruled out). However, it is unlikely that reflections from objects very close to the aerial will be rejected. Fig.8 illustrates reflection from a nearby oblique surface causing an apparent shift of the aerial phase centre (in terms of the far field radiation). Similar shifts will of course occur when switching between aerials mounted at different sites, but these are fixed and can be allowed for.

Fine structure of the radiation patterns due to reflections from highly illuminated surfaces many wavelengths from the aerial will cause rapid fading during aircraft manoeuvres. These fades could affect feedback loop behaviour in adaptive systems, thereby adversely affecting S/N ratios.

## 6 CONCLUSIONS

(1) The total system performance of Navstar GPS obtained from aircraft user equipment will depend critically on the quality of aircraft aerial design and installation. This applies particularly where the aerial system is used to assist in overcoming the effects of jamming. A wide range of aerial system configurations is possible, and all merit further study.

(2) It is considered that effort should be concentrated initially on 'omnidirectional' systems (Categories A and B), and in particular on the development of very shallow profile aerial elements. The use of multimode aerials as a simple means of obtaining some limited anti-jammer performance should also be studied.

(3) The performance of existing conformal three element and six element circumferential arrays developed for AEROSAT (1540-1560MHz) should be examined at the Navstar $L_1$ frequency (1575MHz) and if necessary slight modifications made to optimise the polarisation. This will immediately provide a Category D phased array type of system suitable for sequential receivers, which is already engineered to fly in the RAE BAC 1-11.

(4) Further studies are required on multiple fixed beam (Category C) systems and adaptive systems (Categories E and F), with particular emphasis being given to (a) the design of microstrip patch or similar aerial elements and (b) signal processing for adaptive arrays.

(5) A 'first look' analysis, suggests that, where an aerial system is required with some useful degree of ECCM capability, a Category C system should provide this most cheaply and reliably. No phase shifters are involved, and each directional array or aerial element can be designed for intrinsically low side-lobe levels and good ellipticity ratios. Furthermore the pointing information from which the appropriate aerial may be selected is available in any case from the Navstar receiver, the only extra information required being the approximate aircraft attitude. In adaptive systems, the feedback loop behaviour may be disturbed by 'semi-intelligent' jammer amplitude fluctuation, or due to aircraft aerial radiation pattern fine structure. These considerations do not apply in Category C which relies on the low probability that a jammer will be within a beamwidth of the directions of 3 or 4 satellites simultaneously, a suitable combination of satellites being selected from an average of 9 visible at any one instant. The success of the technique depends primarily on the design of cheap

directional aerial elements or element groups which may be mounted with some flexibility on the outside of a fuselage and cause negligible aerodynamic drag. Printed circuit 'patch', annular slot and crossed slot aerials are promising starters.

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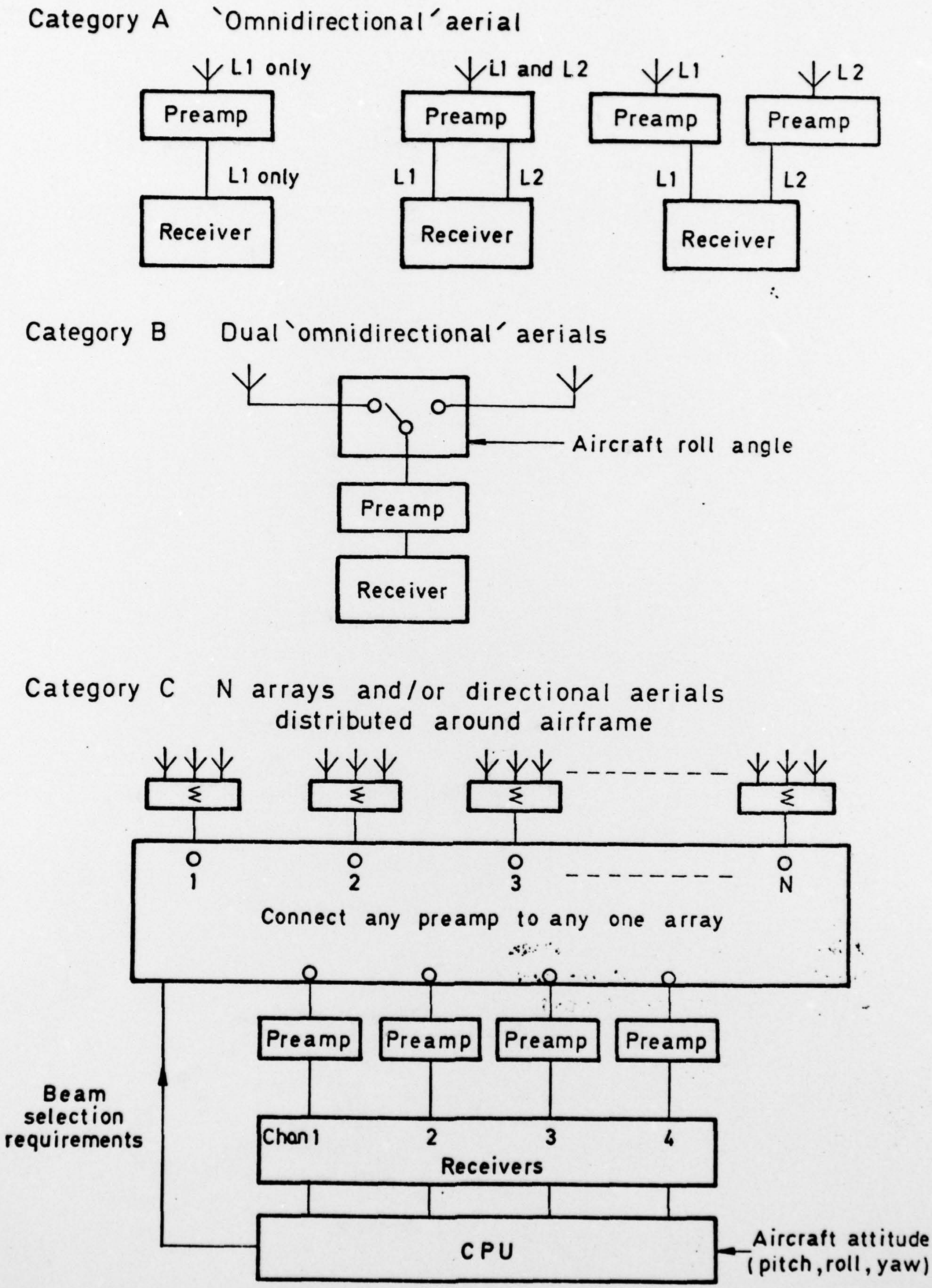
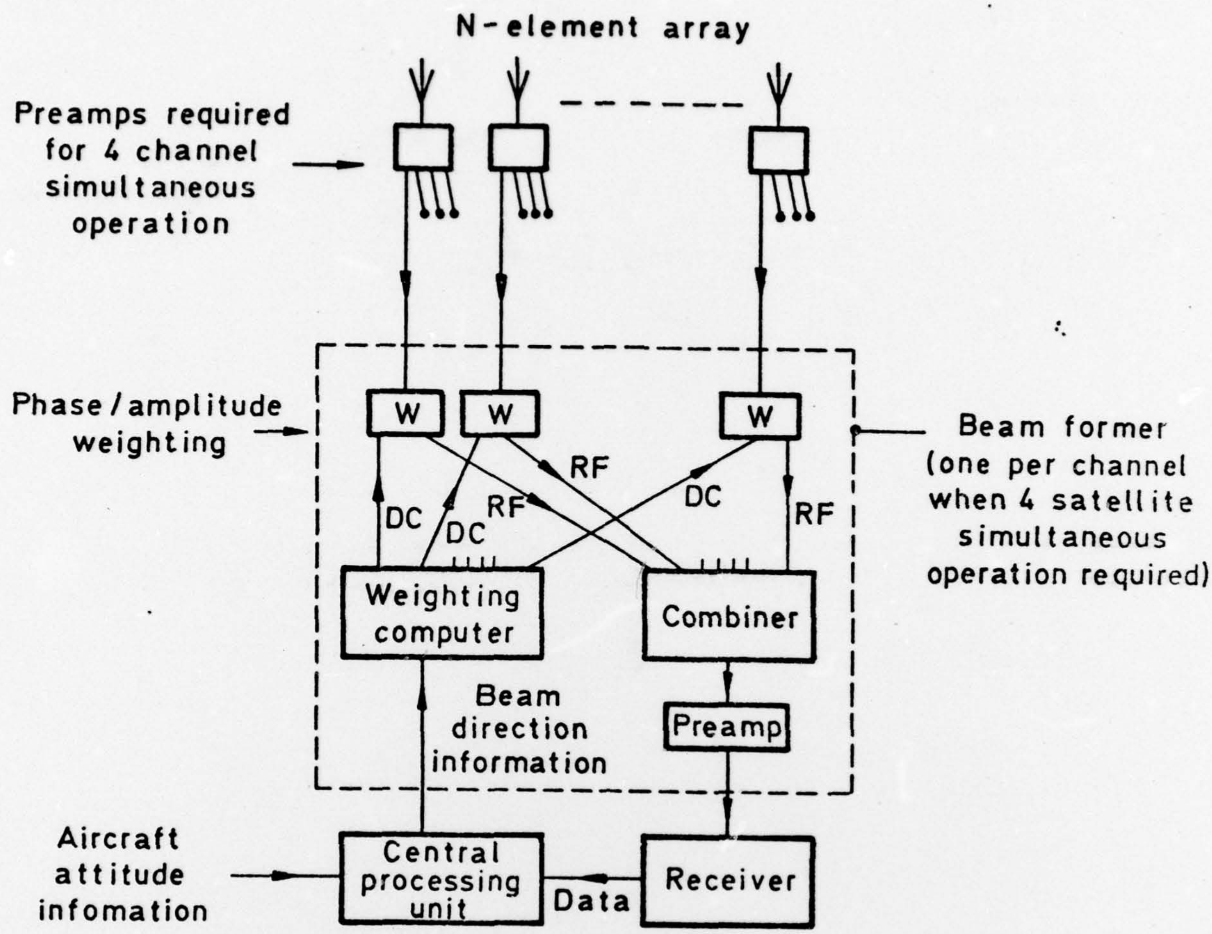



Fig.1 Illustration of aerial system categories

Fig. 2

Category D Geometrically controlled phased arrays




Category E Adaptive null steering array

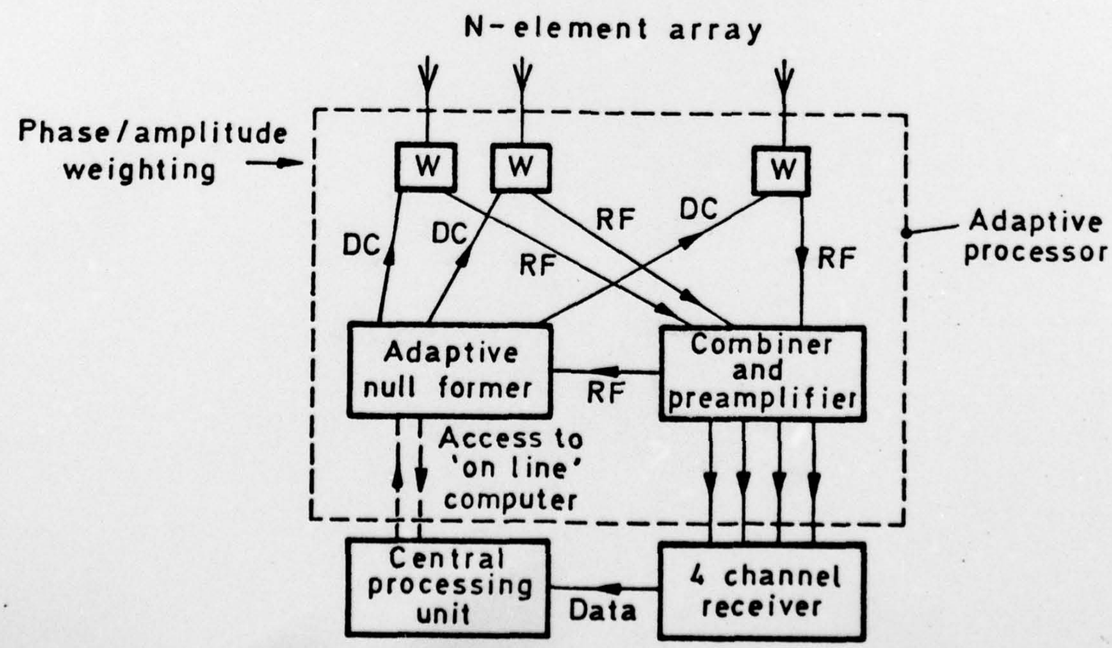
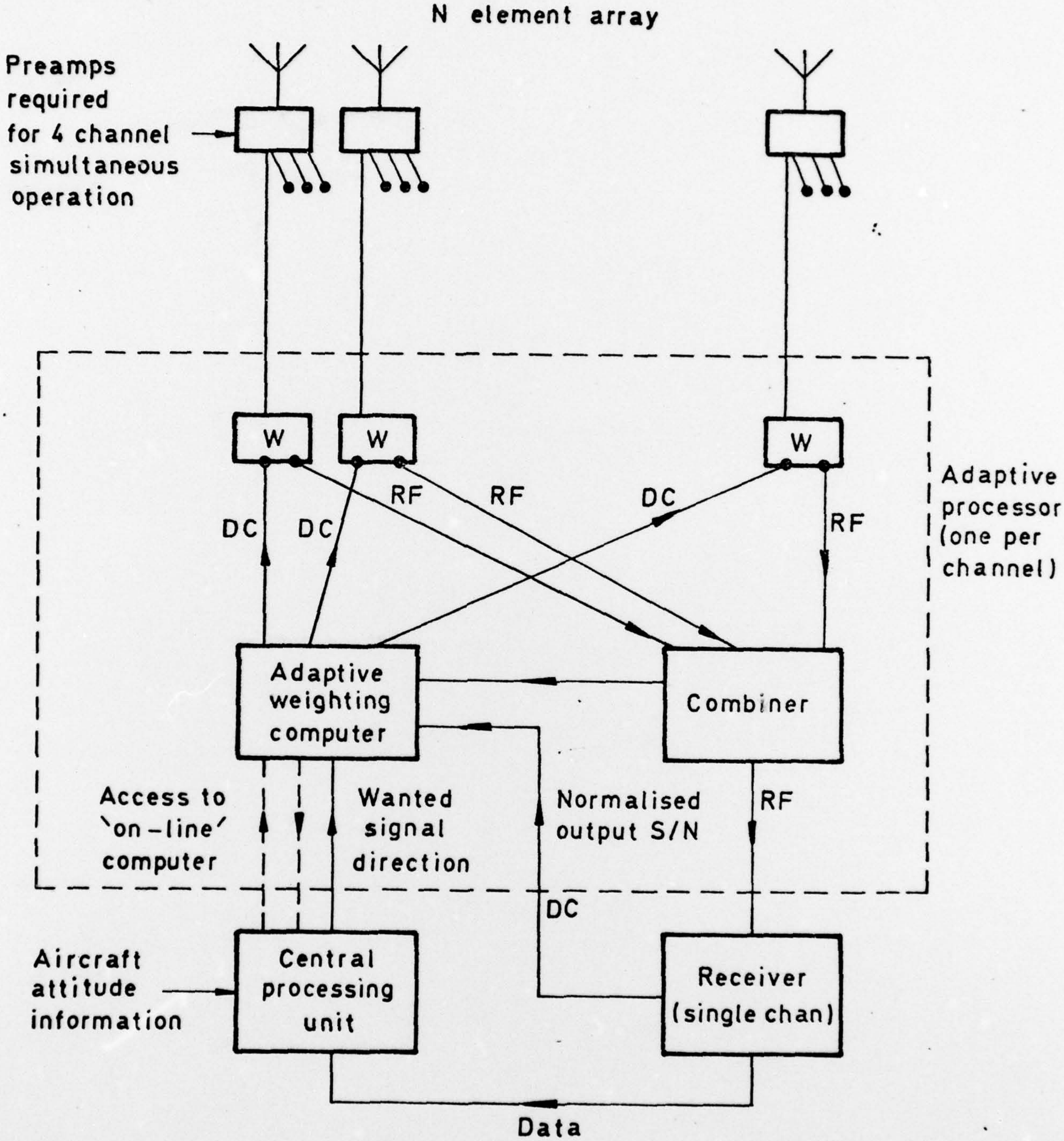



Fig. 2 Illustration of aerial system categories

Category F




Phased arrays with adaptive S/N optimisation

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Fig. 3 Illustration of aerial system categories

Fig. 4

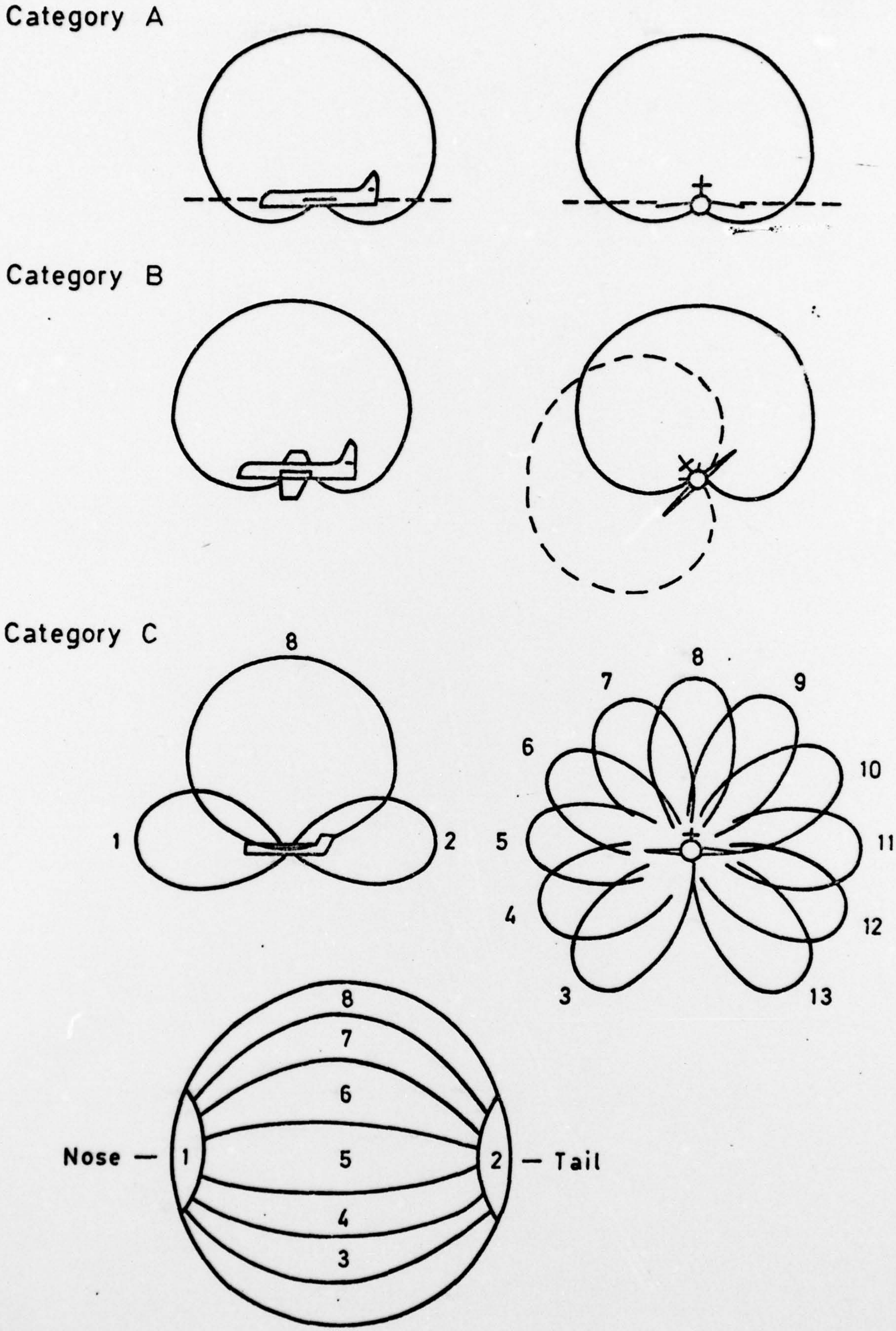
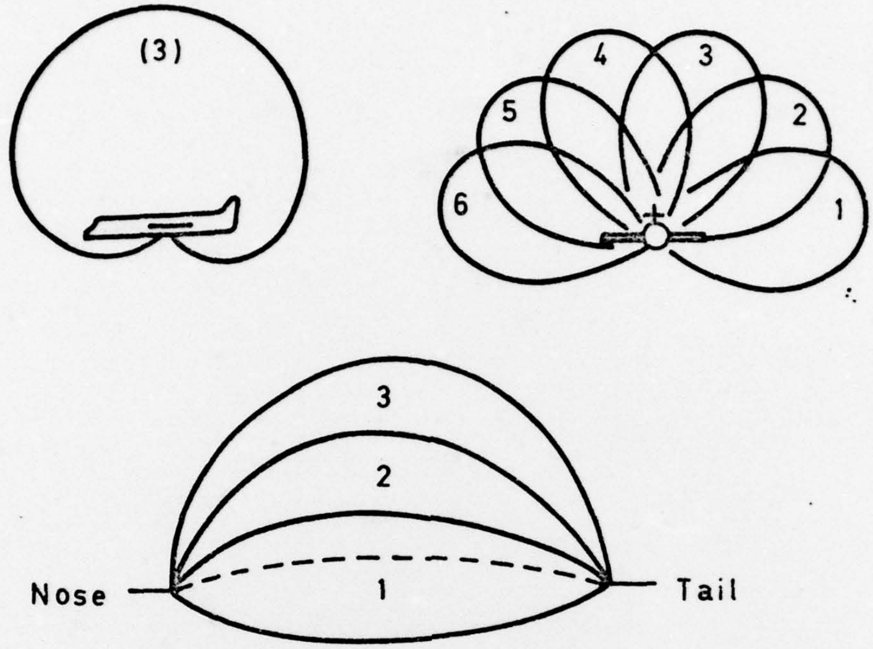
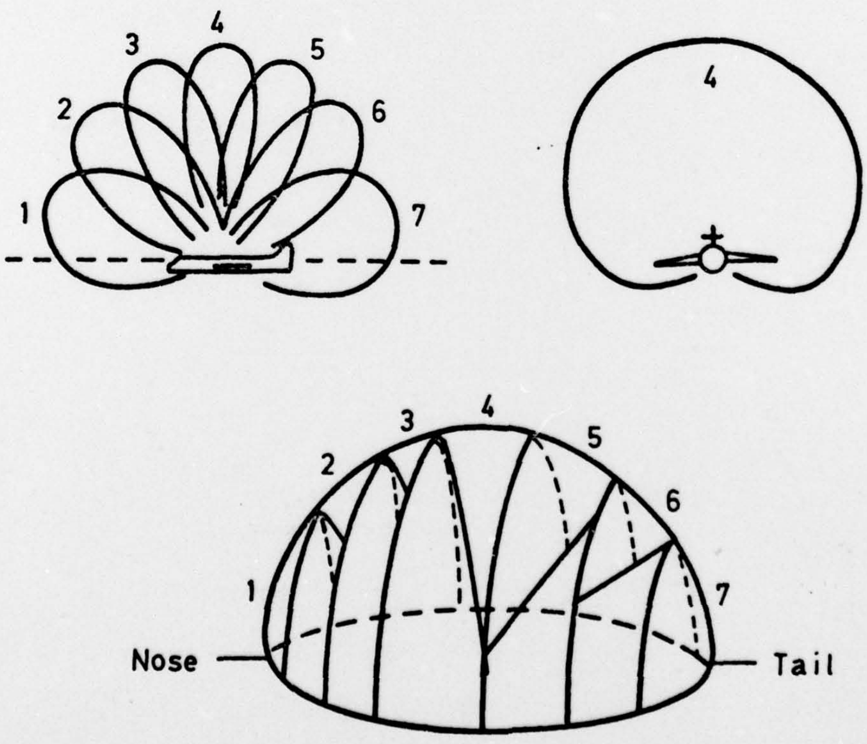



Fig. 4 Illustration of aerial system categories

Category D




a Circumferential arrays

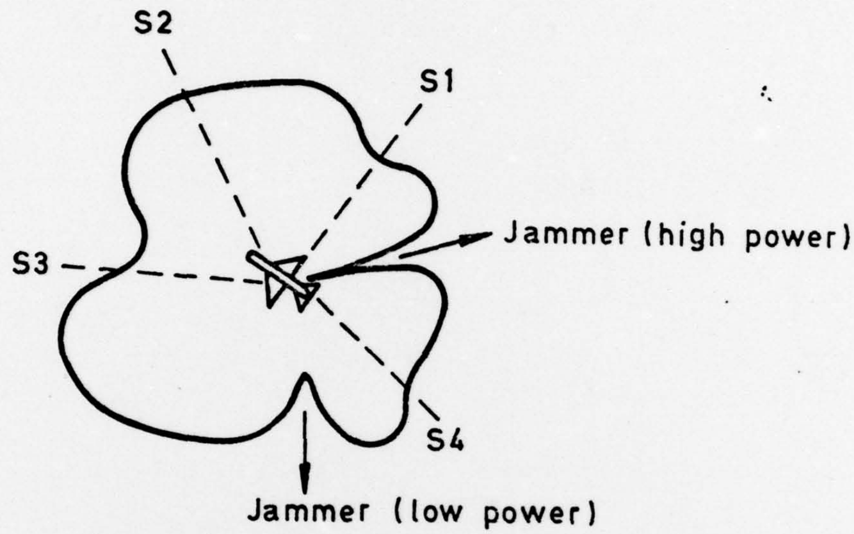



b Longitudinal arrays

Fig. 5 a & b Illustration of aerial system categories

Fig. 6

Category E




Category F

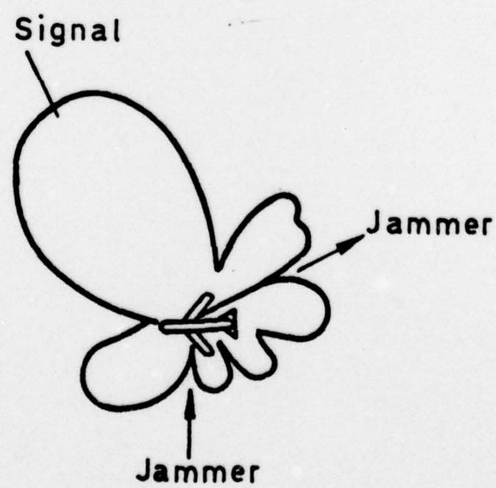



Fig.6 Illustration of aerial system categories

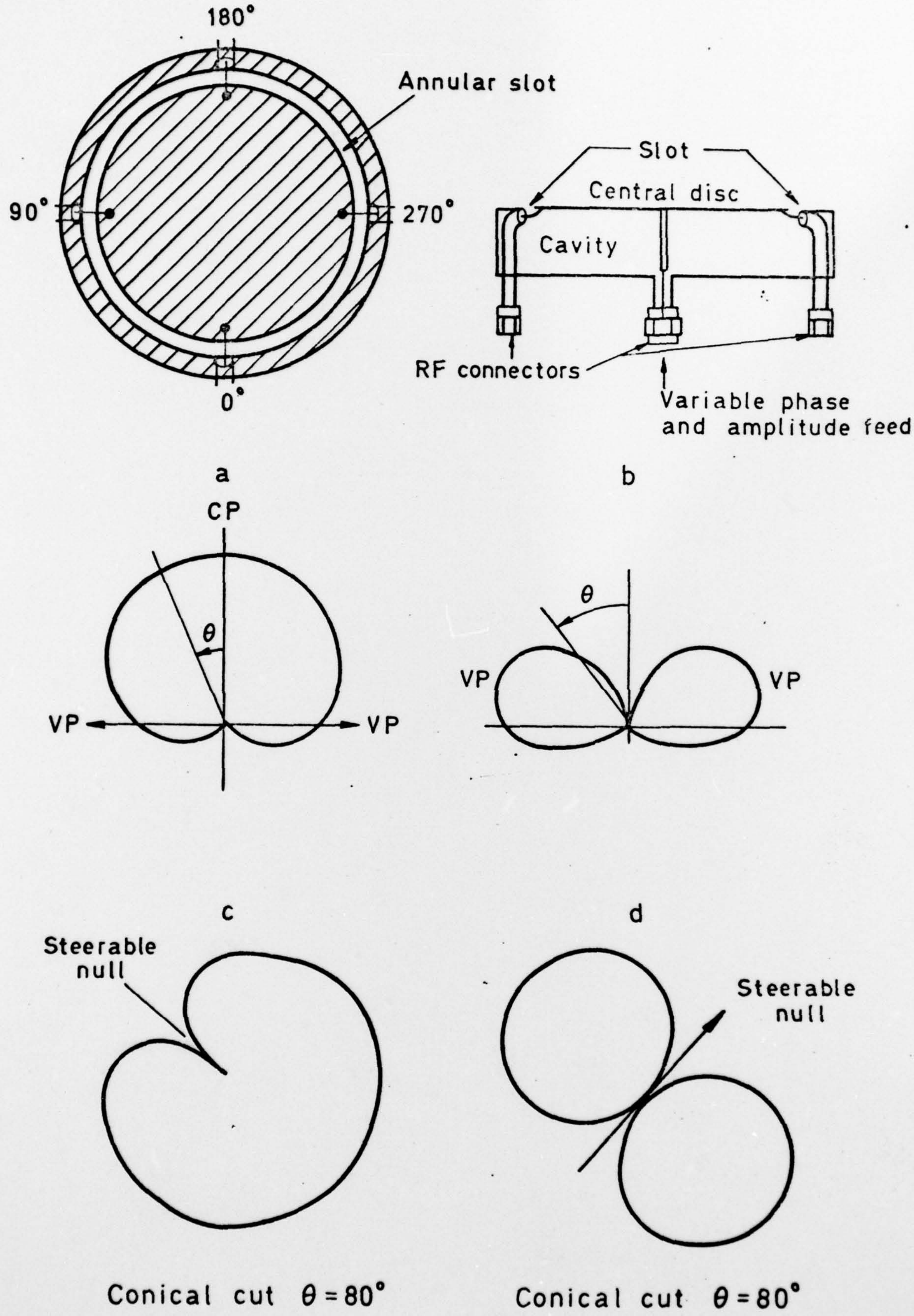



Fig. 7a-d Illustration of multimode aerial

Fig. 8

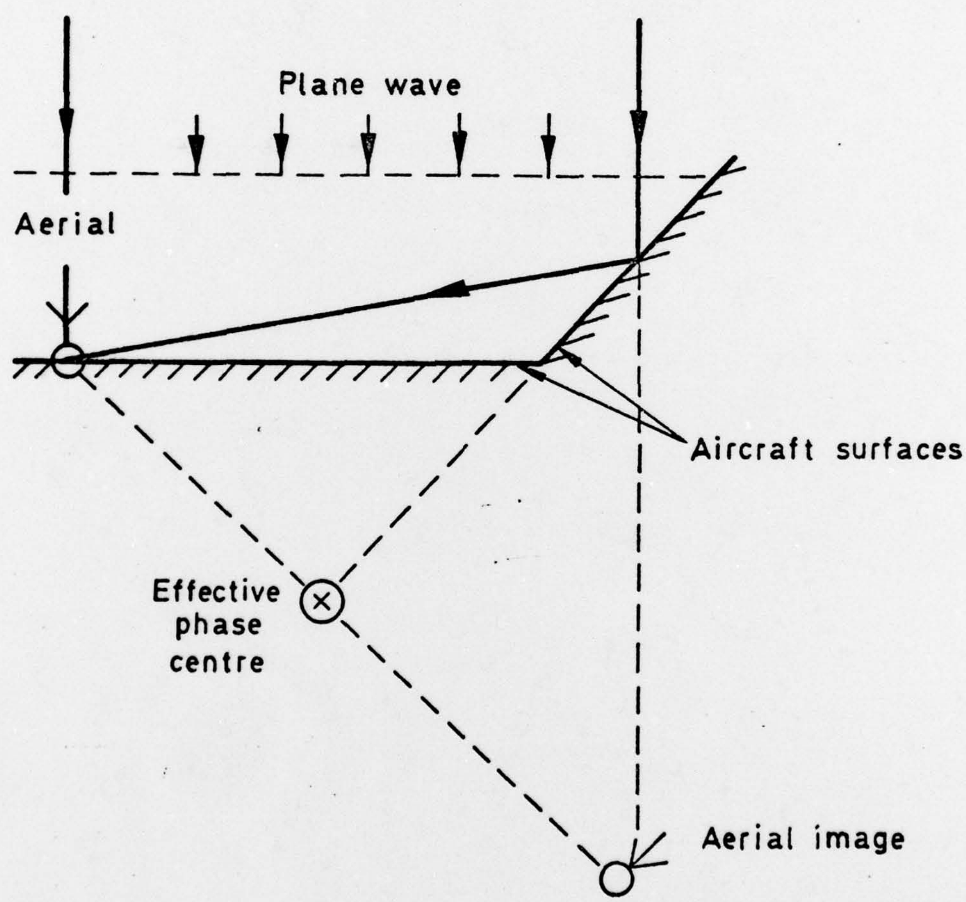



Fig. 8 Illustrating apparent change of aerial phase centre due to reflections

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17. Abstract

Aircraft Aerial Systems for use with the US Navstar global positioning system are categorised, and initial design considerations are given for each category from simple omnidirectional aerials to systems with ECCM capabilities.

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